A NOVEL ANALYSIS OF BRUSHLESS DRIVE SYSTEM WITH ENERGY SAVING MECHANISM

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***Abstract**: In this paper, the brushless DC motor has many applications in the industrial, medical, aeronautical field. A new and improved configuration of converter for brushless DC motor drive with power quality improvements at AC supply mains is introduced. To reduce switching losses associated with VSI a low frequency of switching is used. This is achieved by adjusting the Dc link voltage of voltage source inverter for controlling the speed and commutation of brushless DC motor by electronically. For the voltage control, the converter is operated in discontinuous conduction mode and power factor correction is achieved at AC supply main using a single voltage sensor. The circuit is further modified by introducing a new algorithm for which a brushless drive system can be run in bidirectional direction with minimum Current. The various simulation results are obtained.*

***Keywords**— brushless drive system, Controlling operation, Voltage Source Inverter (VSI), current control.*

1. Introduction

Brushless drive mechanism based motors are widely used in the development of mid-power household appliances, industrial tools, medical applications, etc. Household appliances such as fans, refrigerators, air conditioners, and water pumps use this brushless drive system motor. Advantages such as high ruggedness, good energy-density, high torque/inertia ratio, good efficiency, and low maintenance cost requirements make this motor a good choice for mid-power applications[1]. Brushless DC motor (brushless drive system motor) is a three-phase synchronous motor in which on the rotor side permanent magnets and stator side three-phase winding. For the commutation of brushless drive system motor hall effect sensor is used which senses the position of rotor electronically

For driving brushless drive system motor a combination of the bridge rectifier and DC link capacitor is required [1]. A high total harmonics distortion of supply current at low power occurs due to a high current distortion from supply current when the above combination is used. The design of PFC was done either in continuous conduction mode or discontinuous conduction mode. If the voltage across capacitor or current flowing through the inductor is continuous then it becomes continuous conduction mode else it becomes discontinues conduction mode. For the PFC in continuous mode with voltage control, it requires input current of main (i_{in}), supply voltage of main (vs), DC link capacitor voltage (V_{dc}). As a result, the solid-state switching stress of the PFC converter is reduced but the increases the number of sensors. The operation of discontinuous inductor conduction mode of PFC converter needs only one voltage sensor for the control of voltage and power factor correction. As a result in a discontinuous current of operation the PFC converter's stress increases and, hence suitable for medium power applications [2].

For BRUSHLESS DRIVE SYSTEM motor drive a PFC buck converter has been widely used as a PFC converter. In such a scheme, a constant voltage is regulated at the DC-bus capacitor and a current controller based on pulse width modulation (PWM) which is used for the control of the speed of a Brushless DC motor. The system efficiency is reduced due to the high-frequency PWM signal which causes the switching losses in VSI. These losses in VSI can be effectively reduced by using low-frequency switching pulses for VSI by commutating the brushless drive system motor, electronically. Moreover, for the speed control of the brushless drive system motor, the DC bus voltage adjusts itself. [3].

A new arrangement of the converter is used for DC-DC conversion which shows a good regulation of voltage over a wide range of voltage variation and also acquires high and good light load efficiency [4, 5]. It can also operate as an excellent power factor pre-regulator. A Brushless DC motor drive fed by a

Power Factor Correction converter has been proposed. The bridgeless configuration decreases the front-end converter conduction losses due to the complete and partial removal of DBR but needs a higher number of components [6]. These configurations belong to a non-isolated category, Therefore, this paper investigates a new design of a converter for Brushless drive system motor drive with the reduced number of sensors and power factor correction (PFC) [7]. The circuit is further modified by introducing a new algorithm for which brushless drive system can be run in bidirectional direction with minimum Current.

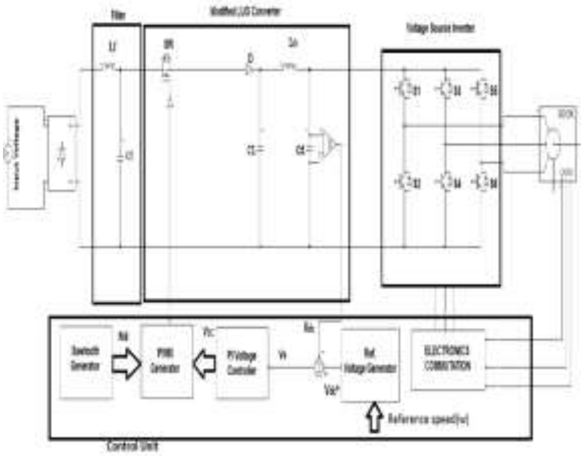

Fig.1. Proposed converter

The Fig-1 shows proposed brushless dc motor drive using a modified converter with a new minimum current algorithm. A diode rectifier followed by a PFC DC to DC converter is used for control of DC bus voltage for improvement of power quality at AC supply mains. To reduce the switching losses the brushless drive system commutates electronically [8]. To reduce the overall cost, the complete operation of drive accomplishes using a single voltage sensor. The designed drive is evaluated at different speeds and different supply voltage [9].

2. Analysis of design

For a Brushless DC motor of 30W, a converter of 25 W (Po) is designed. The DC link voltage is to be regulated from 15V (V_{dcmin}) to 30V (V_{dcmax})
Let the input Voltage V_s is taken as

$$V_s = V_m \sin 2\pi f t = 48\sqrt{2}\sin 314t \;\ldots\ldots\; (1)$$

Where V_m represents the peak value of the input voltage (67.88V), f is the frequency of line i.e. 50 Hz.

The average rectified voltage is obtained as

$$V_{in} = \frac{2\,V_m}{\pi} = \frac{2*67.88}{\pi} = 43.21\text{V} \;\ldots\ldots\ldots\ldots\; (2)$$

The input voltage, as well as output voltage, is related by expression (3), which is given by

$$V_{dc} = d * V_{in} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (3)$$

Where the duty ratio is represented by d.Now using equation (3), the duty ratio for which the designed DC link capacitor voltage of 16 V (V_{des}) results as 0.39 (d_d).

The intermediate capacitor (C_1) is obtained using equation (4) as [6].

$$C_1 = \frac{V_C d_d}{2R_L \; f \Delta V_s} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (4)$$

The permitted capacitor ripple voltage is given by ΔV_C and V_C is intermediate capacitor voltage (i.e.$0.5V_{in}+V_o$). By equation (4), the intermediate capacitor is obtained as 98.8 µF and is chosen as 100 µF for $\Delta V_C = 0.5V_C$.

The equation for L_o the output inductors can be obtained using equation (5) as [6]

$$L_0 = \frac{d_d \; I_{Lo}}{16 f^2 \; C_1 \; \Delta I_{Lo}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (5)$$

The output side inductors current I_{Lo} which is given by Po/V_{des}. Hence, using equation (6) L_0 the output side inductors are obtained for a ripple current value of 2%

$$= \frac{0.39*3.176}{16*((4*10^5)^2*(100*10^{-6})*0.063}$$

$$= 7.6\text{mH}$$

Selected as 8 mH.

By using equation (7) the DC link capacitor (C_d) is obtained as [5]

$$C_d = \frac{I_{omin}}{2*\omega_l * \Delta V_{dcmin}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (6)$$

$$= \frac{1}{2*2*\pi*4*10^5 \;\; *0.045}$$

$$= 100\mu\text{F}$$

Where the I_{omin} is obtained by P_{omin}/V_{dcmin} (where P_{omin} is 54 W, power at DC output voltage of 15 V). $\omega_L = 2\pi fL$, where line frequency is represented by f_L and ΔV_{dcmin} is permissible DC link capacitor voltage ripple which is given by the 3% of V_{dc}. Using equation (6), the DC link capacitor is obtained as 100 µF and it is chosen as 4.4 mF.

C_f is filter capacitance which is obtained such way that its value is lower than a maximum filter capacitive value (C_{max}) and is given by the equation (7)

$$C_{max}=\frac{I_{peak}}{\omega_l * V_{peak}} * \tan\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

$$=\frac{2}{2*\pi*f*48} = 1658nF$$

The peak value of the main supply current is represented by I_{peak}, the peak value of the main supply voltage is represented by V_{peak} and the displacement angle is represented by θ.

Using equation (7), C_{max} is obtained as 1658 nF and therefore, the value of C_f is chosen as 1000 nF.

The filter inductance (L_f) is obtained by equation (8)

$$L_f=\frac{1}{4\pi^2 * f_c{}^2 * c_f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

$$=\frac{1}{4*\pi^2 *(4*10^2)^2*1000*10^{-9}}$$

$$=1.5mH$$

Where f_c represented the cut-off frequency; $f_c=f_s/10$.

3. Controlling the operation of Brushless Drive System

This section is divided into two sub-sections as the control of a PFC converter for adjusting the DC bus voltage with PFC operation and the control for brushless drive system motor to achieve an electronic commutation. This section deals with the generation of high-frequency PWM pulses for solid-state switch (S_w) of the PFC converter. For the control of the Power factor correction converter a voltage follower approach using one voltage control loop is used. A reference voltage for DC bus capacitor (V_{dc}*) is as,

$$V_{dc}^* = k_v\omega^*$$

Where k_v is motor voltage constant and V_{dc}* is reference speed. In order to generate Ve, the voltage error signal the sensed voltage of the DC bus capacitor (Vdc) is compared with the reference voltage Vdc*.

$$V_e(k) = V_{dc}{}^*(k) - V_{dc}(k)$$

kth sampling instant is represented by k

To generated controlled output voltage V_{cc} the error voltage is given to PI controller,

$V_{cc}(k) = V_{cc}(k-1) + k_p\{V_e(k) - V_e(k-1)\} + k_iV_e(k)$ The gains of the PI controller is given by k_p and k_i. The PWM pulses are generated by comparing the controller output voltage with a saw-tooth signal (m_d) of high frequency as,

{if $m_d < (t)\ V_{cc}(t)$ then S_w = 'ON}

{if $m_d(t) > V_{cc}(t)$ then S = 'OFF}

Where Sw1 is the PWM signals given to solid-state switch of the converter.

The position of the rotor is given by

$$\theta = \frac{P}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where is the electrical angle and is the mechanical angle

The inductances and flux linkages is given by

$$\varphi_s = L_{ss}i_s + L_{sr}i_r \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$\varphi_r = L_{rs}i_s + L_{rr}i_r \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The rotor voltages and the stator voltages on the rotor reference frame is given by

$$\frac{d\varphi}{dt} = -Ri - V \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$\frac{dy}{dx} = -R_s i_s - V_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

The total torque developed in the machine is given by

$$J\frac{dW_m}{dt} = T_m - T_e \ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

T_m is the torque of the prime mover.

T_e is electromagnetic torque.

As the inductances keep changing with the rotor position and fluxes and currents are also dependent on the rotor position in this condition the derived various transformation is made use of to convert the linear time-variant system to linear time-invariant system

$$f_a = C_p(\theta)f_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$f_b = C_p(\theta)f_q \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

$$f_c = C_p(\theta)f_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

Where c_p is dependent on

$$C_p = \begin{bmatrix} K_d \cos\theta & K_q \sin\theta & K_0 \\ K_d \cos(\theta - \frac{2\pi}{3}) & K_q \sin(\theta - \frac{2\pi}{3}) & K_0 \\ K_d \cos(\theta + \frac{2\pi}{3}) & K_q \sin(\theta + \frac{2\pi}{3}) & K_0 \end{bmatrix}$$

At steady state, the rotor currents become constant and balanced sinusoidal

$$C\_p^{-1} = \begin{bmatrix} K_1 \cos\theta & K_1 \cos\theta - \frac{2\pi}{3} & K_1 \cos(\theta + \frac{2\pi}{3}) \\ K_2 \sin\theta & K_2 \sin(\theta - \frac{2\pi}{3}) & K_2 \,(\sin\theta + \frac{2\pi}{3}) \\ K_3 & K_3 & K_3 \end{bmatrix}$$

Obtaining the mutual and the self-inductances due to coil on each of the rotor axis having the damper windings q, h, k, and g on direct and quadrature axis respectively.

Stator flux linkages are given by,

$$\frac{-d\varphi}{dt} - \omega \frac{K_q}{K_d} \Psi_d - R_a i_d = V_d$$

$$\frac{-d\varphi}{dt} - \omega \frac{K_d}{K_q} \varphi_q - R_a i_q = V_q$$

$$\frac{-d\varphi}{dt} - R_a i_0 = V_0$$

Rotor flux linkage equations are given by,

$$\frac{d\varphi_f}{dt} + R_f i_f = V_f$$

$$\frac{d\varphi_h}{dt} + R_h i_h = 0$$

$$\frac{d\varphi_g}{dt} + R_g i_g = 0$$

$$\frac{d\varphi_k}{dt} + R_k i_k = 0$$

Obtaining the entire torque developed by the PMSM is given by,

$$T_e = \frac{3}{2} K_q K_d \{ i_q \left[\varphi_d - \left(L_d - \frac{3}{2} L_{aa2} i_d \right) \right] - i_d \left[\varphi_q - \left(L_q - \frac{3}{2} L_{aa2} i_q \right) \right] \}$$

…………… (11)

$$T_e = \frac{3}{2} K_d K_q [\varphi_d i_q - \varphi_q i_d]$$

……………(12)

The Brushless DC motor is commutated electronically which includes perfect switching of Voltage Source Inverter, such that uniform direct current is drawn from DC bus for a 120° and placed uniformly at the centre of back-EMF of each phase. The position of the rotor is sensed throughout 60° by Hall Effect sensors for commutating electronically Brushless DC motor. A new algorithm that consumes less current is introduced in this paper. The algorithm is shown in figure 2

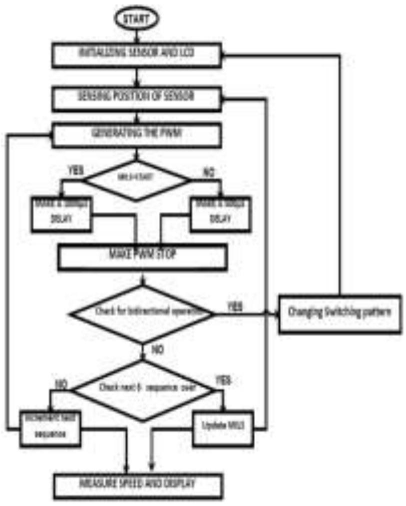

Fig.2.Current Controlling Algorithm

In this algorithm, the output of the Hall Effect sensor is given to the microcontroller. A count is stored in variable start. A timer is started at the beginning of first switching and stops at the end of switching. The value of the timer is compared with the count. If the value of the timer is less than count means the speed of the motor is not high, hence provide a small delay and hence the coils will energized for more time and results to increase the speed of the motor. If the value of the timer is greater than count means the speed of motor high, hence provide a delay since the motor can run with the property of inertia, so the coils are too energized only a few times. The main advantage of the proposed algorithm is that it draws only a few currents compare to the previous algorithm. It draws only 200mA. Bidirectional operation is done by changing the switching sequence.

The simulation diagram of the proposed Brushless drive mechanism based motor drive is shown in figure 3.

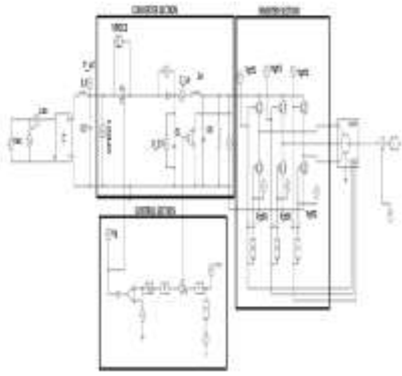

Fig.3. Simulation of the proposed brushless drive system System

The simulation is done for speed of 300rpm. The input current and voltage is shown below

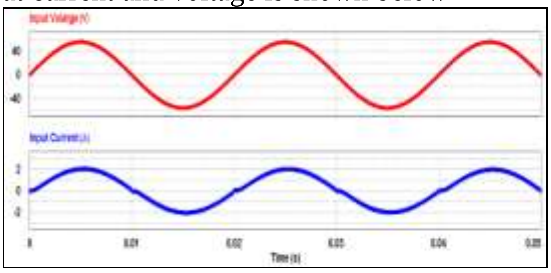

Fig.4. Input voltage and input current

The input voltage is 48V AC and the input current is obtained as 2A. From the graph, we can see that the input voltage and input current are in phase so the converter itself acts as a power factor correction circuit.

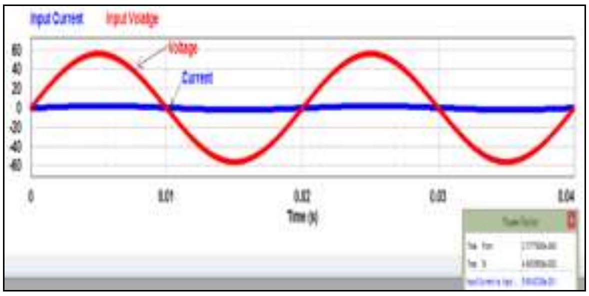

Fig .5. Power factor

The power factor is obtained as 0.98. Figure 6 shows switching pulses of VSI

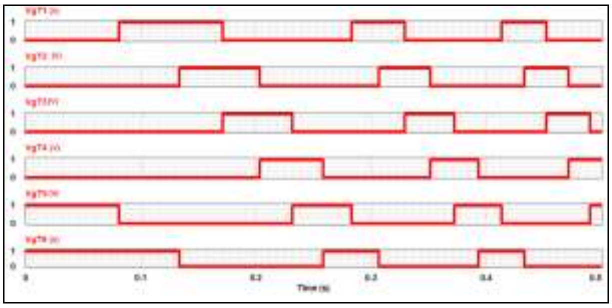

Fig .6. Switching pulses of VSI

Six MOSFET switches are used in voltage source inverter. At a time only two switches are ON state, remaining is OFF state. The voltage waveform of the capacitor C_d is shown in figure 7.

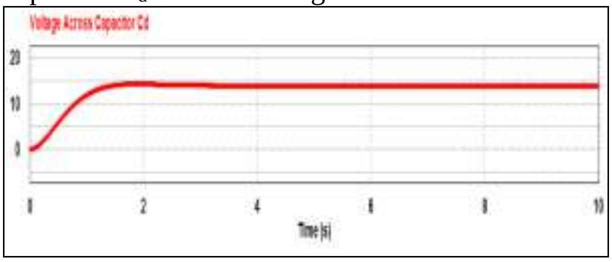

Fig.7. The voltage across capacitor C_d

The voltage across the capacitor is about 15V. The capacitor voltage becomes steady after a time of 1s. From the graph, it can be inferred that the V_{dc} voltage i.e the V_{dc}, DC link voltage is almost ripple-free. In Fig. 8 shows the waveform of speed in RPM

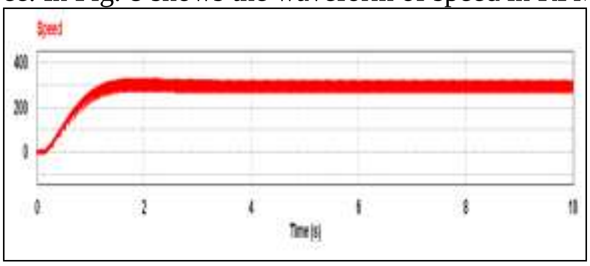

Fig.8. Speed of BRUSHLESS DRIVE SYSTEM motor

The speed of the motor is obtained at 300rpm. From the graph, it can be inferred that the presence of ripples. The speed ripples obtained at 14rpm. The torque waveform is shown in fig 9.

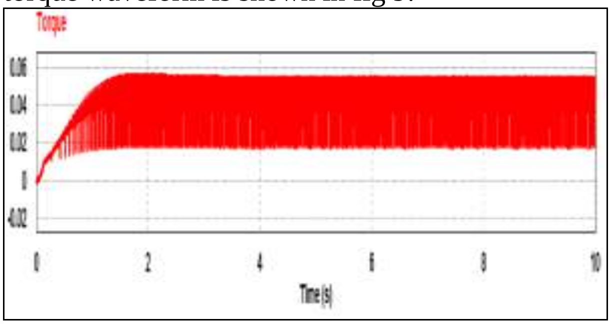

Fig.9. Output Torque

The torque is obtained as 0.05NM. Torque contains some ripples which is about 0.038NM.

4. Conclusion

A new configuration of an AC to DC converter has been proposed in this work for feeding the BRUSHLESS DRIVE SYSTEM motor drive. The operation of the proposed drive has been realized using a single voltage sensor. An approach of variable DC link voltage has been used for adjusting the speed of a BRUSHLESS DRIVE SYSTEM motor. Moreover, switching losses in six MOSFET switches of VSI has been reduced by electronically commutating Brushless DC motor such that the Voltage Source Inverter operates in low-frequency switching. The proposed converter reduces voltage stress, current ripple comparing to the conventional converter. A new algorithm is proposed in which motor works in reduced current operating mode.

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